THE SOUND OF ROWING STROKE CYCLES AS ACOUSTIC FEEDBACK

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ABSTRACT

Acoustic feedback offers promising opportunities to enhance the perception of athletes in regards of the modification of movement patterns and control in technique training. Sound conveys time-critical structures that are perceived subliminally, which is of crucial importance for the precision when modifying movements to improve their execution. Technological advances allow the design of innovative feedback systems to communicate information audibly to athletes. This paper describes a concept for providing acoustic feedback online during on-water training sessions to elite rowers with the final aim to improve the mean boat velocity by a reduction of intracyclic interruptions in the boat acceleration.

Following the initial analysis of technical and biomechanical requirements, the acoustic feedback system *Sofirow* was designed and field-tested with elite athletes. This rowing specific training system presents the boat acceleration-time trace audibly and online to athletes and coaches. The results showed a significant increase in the mean boat velocity when the acoustic feedback was used compared to sections without. It thus seems promising to implement acoustic feedback regularly into training processes for elite athletes. A behavioural dynamics approach was recommended to provide a theoretical basis for this concept.

1. INTRODUCTION

Everyday situations ubiquitously generate acoustic information that also includes the context of sport situations, considered as the result of temporarily sequences of events. Interaction of materials causes sounds that represent physical characteristics such as size, shape and/or distance audibly. In principle, it is data that is synthesized. Different attributes were represented in the sound result via basic acoustic elements like loudness, pitch, duration of the acoustic event. Thus, sound basically is the acoustic consequence of kinetic events that is grounded on its shared physical nature which is an inherent time structure. The existence of that inextricable relationship was described several times before [1], [2].

Since the era of ancient Greeks, it has been known that movements epitomize this alliance and that has influenced human movements in all known cultures as a social function. It was assumed that music evolved as a cooperative method for the coordination of actions and promotion of group cohesion [3].

Research in neuroscience provide evidence to the (unique) influence that acoustic stimuli has on humans to drive rhythmically and metrically organized motor behaviour [4], [5] and which is enunciated in a strong connection between sensory input and motor output [6]. By receiving only the raw (but essential) data via acoustic sensations, it is the translation and organization by the brain into meaningful information. The relationship between sonic energy and meaningful acoustic information is covered by the sound and human communication chain followed by a twofold regard of perceptional aspects as well as of the sound design. The implementation of synthetically generated acoustic information (sonification) for purposes of movement facilitation widened this chain for the action aspect (i.e. that sound proceeds over time) that is also known as "procedural audio" [7]. Thus, it is considered as a living sound effect that can be changed in real time and accordingly to unpredictable events. Consequently, it is part of an interactive process. This interaction between perception and action is an active process during the movement execution, in particular in regards of the modification of movement patterns and control. It is a pivotal question in the practice of sport as well as in applied research in the field of motor control and learning.

To understand this process of sound-perception and action-modification it requires a coherent theoretical background that examines aspects of internal perception as well as aspects of movement organization and coordination. Since knowledge increased in biology and neuroscience during the past twenty years in particular, new ways of understanding human beings and their interaction, including the nature of human perception, communication and finally behaviour has developed. Such an understanding of perception is considered as a process of apprehending the objectivity reality of the world.

The theoretical background used here is provided by an approach labelled as *behavioural dynamics* according to Warren [8]. But in contrast to his classic information-based approach, an ecological-based approach to perception was chosen that was integrated with a dynamical systems approach to action. In this sense, sound is considered as a process rather than as data. Omnipresent in the environment, sound is used most of the time unconsciously by humans during their interaction with the world. Specifically, time-critical structures in the sound are perceived subliminally. In other words, the information contained in the sound is not always explicitly processed; it is rather perceived as a side effect. That is of crucial importance for the precision when modifying movements in regards of improving its execution. Another outstanding advantage of acoustic information is its supportive function for improving the effectiveness in interaction without distracting listeners' focus of attention. Moreover, the sound supports the concentration on specific sections in the sound selectively by simultaneously perceiving the sound as a whole [9].

Early investigations in the field of sport science used the strong audio-motor relationship by providing acoustic feedback to athletes in order to sensitize them to the time-dynamic structure of the movement (e.g. in tennis, javelin throwing, hurdle run, swimming and ergometer rowing). With the ongoing progress in technology, new ways are opened to design innovative feedback systems and tools providing information audibly. Research in computer science (among others) recently has contributed to this development providing successful experiments in several domains such as in a single case study in speed skating [10]. The presentation of additional given acoustic information becomes especially interesting for technique training and control in elite sports, as it is helpful in cases in which the visual perception-channel is busy and already blocked as it can be received as a side effect.

In rowing, acoustic feedback is a new and promising application to optimise the boat motion as well as to supplement the existing feedback systems that have been used successfully in the German Rowing Association (DRV) for more than ten years [11].

Since first considerations in regards of both, basic technical requirements (sound design) as well as biomechanical aspects (displayed parameter) [12] have been realized, the acoustic feedback system *Sofirow* (*So*ni*fi*cation in *row*ing) was designed for on-water rowing training and field-tested with elite athletes. The device presents the boat acceleration-time trace audibly and online to athletes and coaches. The idea behind this approach aims to enhance the perception of the movement in order to provide assistance for the development of a feeling for the movement within the process of embodied cognition and entrainment. Taking advantage of auditory perception, it was assumed in accordance with Spitzer, that someone, who wants to feel, must listen. Modifying this assertion, it was supposed, that someone who hears can have a better sense of feeling. With that assumption, an enhanced feeling for the rhythm of the boat run is meant to improve the mean boat velocity.

Empirical evidence for a supporting function of sounds in all its formats already exists from various research fields. It was assumed that acoustic feedback has an effect on the time structure of the rowing cycle, particularly during the recovery phase. Primary focus was set on analyzing athletes' perception of the sound result in regards of functionality and aesthetics as well as on the effect analysis.

2. METHODS

2.1. Characterization of the rowing cycle

The rowing stroke is a cyclic motion sequence which is commonly separated into two main phases drive and recovery (or release), which are further subdivided into the front and back reversal (also known as the catch and finish turning points). With regards to the boat acceleration-time trace, the rowing cycle begins with minimal acceleration followed by a distinctive increase during the catch and the drive phase to the point of maximum boat acceleration. The next local minimum in acceleration represents the end of the drive phase. Strictly speaking, that is in parallel the transition phase where the oars were lifted out of the water (back reversal). The recovery phase begins subsequently to the transition phase with minimal acceleration amounts and ends with again with a minimum in acceleration. It is subdivided into a first and a second phase. In doing so, the classification of the several phases in the rowing cycle is realized in relation to a description of the rowing movement as well as of the executed movement technique.

The primary and outstanding importance of the recovery phase becomes evident with regards to propulsive aspects of the rowing cycle. At the end of the drive phase, when the blades emerge from the water, the boat is released to run forward. This movement is challenging for the athletes after raising the oars out of the water, as they have to glide back up to the catch again in order to prepare the next stroke. Thus, it is important to execute the recovery phase without reversing the boat's momentum, that is, athletes' mass must be carefully slid towards the stern. This phase is critical for the boat velocity in particular because fluctuations occur as a result of energy dissipations by jerky movements. Consequently, athletes are supposed to integrate the several parts of the rowing stroke into one movement that is as consistent and smooth as possible. This is especially important because one movement phase flows into the next one. Specifically, when rowing at higher stroke rates it is not possible to strictly separate the single movement phases from each other.

2.2. Subjects

The participating athletes in the study were members of the German junior national rowing team (*N*=23), male (n=18) and female (n=5). Average age was 17.8 years (±0.7) (♂) and 17.6 years (±0.6) (♀). Anthropometric data of the male: body height 193.4cm (±4.1) and body mass 87.8kg (±4.2); female: body height 175.0cm (±6.0) and body mass 67.2kg (±8.2). In the investigation six boats in different boat categories (small and big boats) have been considered in up to five training sessions that were labelled as follows:

junior single scull, female (JF1x)
junior coxless pair, male (JM2-)
junior double scull, male (JM2x)
junior coxless four, male (JM4-)
junior quad scull, female (JM4x)
junior eight, male (JM8+).

2.3. Measurement System

In order to create acoustic feedback, the training and measurement system *Sofirow* was developed in cooperation with engineers from BeSB GmbH, sound and vibration, Berlin. The device measured the kinematic parameters: propulsive boat acceleration (a_{boat}) with a micro-electro-mechanical (MEMS) acceleration sensor (sampling rate adjustable up to 125Hz) and boat velocity (v_{boat}) with GPS (4Hz). Figure 1 showed the system and its position location on top of the boat.

The boat's acceleration-time trace was converted into acoustic information and transmitted via WLAN online to the athletes in the rowing boat. Athletes received the acoustic feedback wearing earplugs or via loudspeakers which were mounted inside the boat. Selective online control of the sound in terms of timing and duration as well as modulation of tone pitch and sound volume was possible by remote-control from the accompanying motorboat of the coach.

Figure 1: The training and acoustic feedback system *Sofirow*.

The transmission was switched on and off by the scientist in agreement with the coach who could receive the same acoustic feedback simultaneously online in the motorboat. The data storage on a SD-card made it possible to analyse the effect of the acoustic feedback on the boat motion in real time as well as to re-sonify the data subsequently.

2.4. Sound Design

The sound result was created by a transformation of the boat's acceleration-time-trace that was derived from its physical parameters using the software Pure Data (Pd). To convert the data into a meaningful sound result, the sonification method of Parameter Mapping [13] was chosen. In doing so, every data point (acceleration value) was mapped to a tone on the MIDI-scale (electronic musical scale) and related to tone pitch. Specifically, every whole number (integer) corresponded to a specific semitone according to the MIDI-scale. Middle C on the western musical tone scale represented the point of zero boat acceleration; positive and negative acceleration values varied above and below this tone pitch. Thus, the data were transformed algorithmically into an audible sound, and, most important for the modification of the movement in real time, there was a direct modulation that produced movement-defined sound sequences as the outcome. Consequently, tone pitch changed as a function of the boat's acceleration-time-trace and represented and differentiated qualitative changes in the boat motion.

2.5. Test Design and statistical analysis

The investigation took place at the race course in Berlin Gruenau in June/July 2009 during the preparation phase for the junior world championships. The measurements involved alternatively changing sections without and with the presentation of acoustic feedback for the duration of 3 to 5 minutes. In order to conduct an online analysis, the scientist and the coach listened to the sound result in the motorboat while the athletes did not receive any feedback. For the analysis, the sections were separated, consisting of a total of 30 rowing cycles each rowed at a comparable stroke frequency (±0.5 strokes per minute) for all boats. The effect analysis was realized by an intra-cyclical examination of the acceleration curve in relation to the phase structure of the rowing cycle with its rhythmical division into the two main phases drive and recovery. The data for the analysis was taken from the junior men's eight (MJ8+).

In doing so, several events were defined inside the acceleration curve that was represented by zero points as well as local and global extreme values which have been identified with special developed software and calculated as points in time. Thus, the time structure of the acceleration curve was analysed. Moreover, the differences between the time points were calculated and labelled as time intervals. Statistical comparison was achieved using an ANOVA (general linear model) with repeated measures (level of statistical significance was set at $p<0.05$) with the software SPSS 16.0. This procedure allows the test of interdependencies as well as of impacts (effects) from single factors between the sections studied.
Additionally, standardized questionnaires were taken to examine athletes' perception of the acoustic feedback in terms of its comprehensibility, correspondence with the rowing movement and attention-guidance function for specific movement sections.

Finally, an analysis of the sound results (audio files) was made with spectrograms to visualize the acoustic properties that represented the physical characteristics. Spectrograms (also known as sonagrams) were commonly used to identify acoustic signals through visualisation of the sound spectrum and in order to analyse its spectral density over time. The graph is displayed in two (or sometimes three) dimensions, indicating time (x-axis), frequency (y-axis) and amplitude (z-axis) of a particular frequency at a particular time that is represented whether by the colour-intensity or colour of each point in the graphic. The spectrograms were created with the software Adobe Audition 3.0. Sonifications of the sections with and without acoustic feedback were presented.

3. RESULTS

3.1. Data

The results showed a significant improvement in the mean boat velocity for all boat categories in the sections with acoustic feedback immediately after the sound was presented ($F_{2.38}=36.6$; $p=0.00$). In principle there was no difference found between the crews in the way the sound affected them which is displayed in the interaction diagram (figure 2) with the mean individual developments of the boat velocity for the sections studied in comparison for all boats.

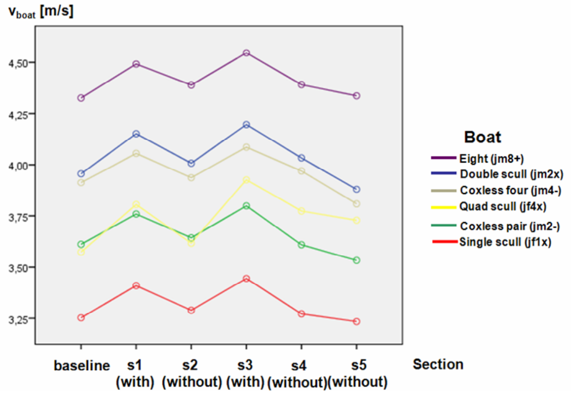

Figure 2: Interaction diagram for the boat velocity for the sections studied for all boats in comparison.

An intracyclic analysis of the rowing stroke for the individual case of the junior men's eight showed a significant reduction of the time intervals between the events (points in time) in the boat's acceleration curve (F_1=94.54; p=0.00). The single profiles of five rowing cycles each demonstrated the differences between the sections without and with acoustic feedback (figure 3). The second part of the recovery phase ("1" in figure 3, lower) as well as the front reversal ("2" in figure 3, lower), in particular, were affected. Thus, it was possible to confirm our initial assumptions that acoustic feedback provides assistance for the athletes to enhance their perception for executing the movement.

As expected, the differences between the sections without and with acoustic feedback was audible in the acoustic mapping of subsequently sonified data. In more detail, the sound sequences of the section with acoustic feedback differed from the section without in terms of tone pitch and duration before the tone lowered ("1" in figure 3, lower and audio files labelled as *with AF* and *without AF*). This happened as a result of a more carefully controlled movement by the athletes when sliding with the seat. Consequently, there was a reduction of the duration of negative boat acceleration ("2" in figure 3, lower) because athletes started later to realize the front reversal.

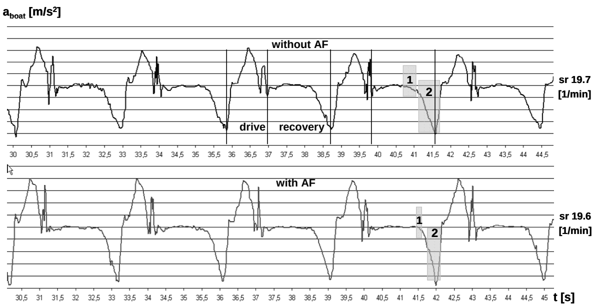

Figure 3: Five single rowing cycles of MJ8+ for the sections without and with acoustic feedback (AF) in comparison. [sr=stroke rate].

A visual comparison of the audio files by means of the spectrograms confirmed an improved, more uniform and homogenous movement execution showing less variation inside the acoustic spectrum (figure 4). These findings give support to our initial assumptions that acoustic feedback provides assistance for the athletes to enhance their perception for executing the rowing movement more effective.

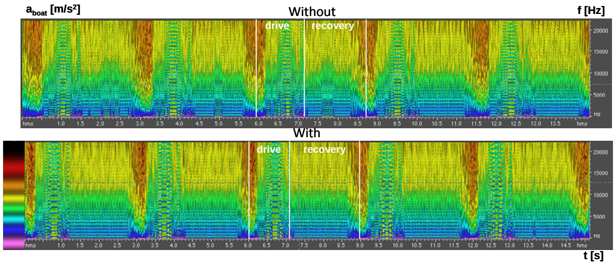

Figure 4: Spectrograms for the sections without and with acoustic feedback in comparison for five rowing cycles each.

3.2. Questionnaire

The results of the questionnaire showed overall positive reaction with regard to the acoustic feedback experienced among the athletes. Its supporting function during the movement execution in on-water training was confirmed and thus, the concept received high acceptance among the athletes as well as among the coaches. The reproduction of the boat motion was recognisable. More precisely, characteristic phases of the boat's acceleration-time trace were perceived as changes in tone pitch within the single rowing strokes as well as between the stroke series.

"The sound pointed to things of which we have not been aware before and we became more conscious of the movement."

The sound correlated with the individual kinaesthesia of the athletes in correspondence to the movement execution.

"The sound evokes the movement."

That intensified the imagination of an optimal execution of the movement by perceiving the sound as an audible reflection of a consistent and smooth realized movement. With that, athletes' focus of attention was guided via the sound to specific sections within the rowing cycle, particularly to the second part of the recovery phase and the turning points.

"It is audibly very clear that the sound is reduced during the slide-movement. Consequently, we tried to avoid the sound to become silent."

As a result, the control of the recovery phase in particular was improved.

"It is possible to control mistakes directly, such as in cases in which placing the blades was too slow."

The sound did not interfere with athletes' normal perception. In doing so, athletes preferred the presentation of acoustic feedback via loudspeaker, being able to perceive the natural soundscape of rowing in addition to the synthetic acoustic feedback. In contrast, transmission via earplugs or headphones isolated the athletes from sounds they were used to hear during rowing.

"The natural sounds of the boat have to be audible in order to relate the movement to them as soon as the loudspeaker has been removed."

It became evident that functionality of the sound sequence dominated over aesthetic aspects for the purposes of practical use in the daily routine of on water training sessions. As a direct and pure (valid) mapping of the information contained in the boat's acceleration-time trace which was intuitively comprehensible to both athletes and coaches.

"It doesn't matter how it sounds, the main thing is that differences between high and low acceleration become audible."

Most of the athletes would appreciate a regularly use of Sofirow as a promising training-aid.

4. DISCUSSION

This paper described a concept for providing acoustic feedback online during on-water training session to elite rowers with the objective of enhancing athletes' perception for movement execution. The final aim was to improve the boat velocity by a reduction of intracyclic interruptions in the boat acceleration. A theoretical basis for the concept was recommended with a behavioural dynamics approach, as well as a design for an acoustic feedback system as rowing specific training system and for its implementation in on water training sessions.
Therefore, the boat's acceleration-time trace was analysed and described acoustically (sonified) for the purposes of making audible the measured differences in movement intensity. Online generated sound characterised (differentiated) the rhythm of the rowing cycle by its relation to tone pitch. Accordingly, every change inside the boat's acceleration trace was acoustically represented, also revealing those changes that were neither visible by solely looking at the single profiles of the rowing cycles (figure 3) nor by watching the boat travelling through the water. Thus, the direct data mapping and the changes or reversals in the boat's momentum (interruptions) became apparent in the sound. To demonstrate this fact in more detail, a video of a training section was taken in a preliminary study and synchronized with the sonified data sequence of the boat's acceleration-time trace using the example of the junior men's coxless four (JM4-) [14].

In summary, the acoustic feedback reflected overall effects of all external forces (water resistance, etc.) as well as athletes' movements acting on the system as a whole (boat and rower). With that, different intensity steps and boat categories (big and small boats) showed different profiles of the boat acceleration-time traces and so, different acoustic profiles.
Using the training-system *Sofirow* in on-water rowing training sessions demonstrated the possibility for altering the mean boat velocity as well as the acceleration-time trace intra-cyclically within a single stroke as well as within a stroke series when acoustic feedback was provided.
As assumed initially, the extension of the recovery phase in the section with acoustic feedback showed an increased positive boat acceleration that occurred as a result of improved crew synchronization. Athletes perceived the sound information of the movement patterns independently from vision and thus, the medium of presentation was supportive and enhanced their perception of the boat run. Interactivity of the perception process was allowed within the time frame of neuronal information acquisition and processing [15]. As a result, the control of executing the movement was realizable in a time-uncritical way. Moreover, the psychological interaction between the coach and athletes was bridged as the sound result was intelligible to all in contrast to the coach's verbal instructions that sometimes need further explanations.
Owing to the direct coupling of tone pitch to changes in the boat's acceleration-time trace, the information contained in the measured data became intelligible for the athletes, directly and intuitively. Thus, athletes perceived the single rowing cycle as a short sound sequence that repeated with its characteristic phases and with every rowing cycle. That is comparable to the refrain in a piece of music as tone pitch is defined as "the perceptual correlate of periodicity in sounds" [16]. Periodic recurrence of characteristic sections inside the rowing cycle as sub-parts of the total cycle awakened a sensitivity for details in the sequence without further explanations needed. Awareness of the structure emerged solely from the knowledge of the movement and audio-visual interaction. The changes perceived in tone pitch occurred as the representation of variations inside the single rowing stroke as well as of variations between the cycle series.
In movement science rhythm is defined as a temporarily sequence of motor actions whose timing is crucial for a successful executed movement. Thus, rhythm and synchronisation is inseparable in a moving context. Consequently, it was assumed that the measured improvement in the mean boat velocity was due to both, an improved crew synchronisation as well as due to an improvement of the individual rowing technique of the athletes. This was confirmed on the one hand due to the fact that the improvement was measured for all boats including the single scull and on the other hand due to athletes' individual statements.

5. CONCLUSIONS

The training system *Sofirow* supported the control of the rowing movement by the presentation of a feedback signal that is provided through the sense of hearing in addition to existing sensory channels as well as in addition to existing feedback systems. Captured sonified data of the boat's acceleration-time trace are stored as audio files (wav file format) and available for a mental preparation for training session and/or competitions. Moreover, it offers acoustical comparisons of training sessions and race phases (such as the start phase).
The advantages of acoustic feedback make it possible to incorporate sound (i.e. sonification) into the training of elite athletes in order to assist the execution of movements and thus, to optimise them. This offers new possibilities, especially for motor control and motor learning as well as for the development for a feeling of the rhythm in racing boats. Coordination that is described as the most challenging factor influencing the rowing performance - besides force and endurance - [17] is enhanced in addition, for both, the coordination between athletes (interpersonal) as well as within the single athlete (intrapersonal). Crucial aspects of the technique training were addressed because the reproduction of several movement patterns is facilitated and monitoring is made easier [18].

However, there are still questions that remain open and which have to be clarified in further investigations, planned for the current year. In particular, there are questions in regards of the practical implementation of acoustic feedback during on water training sessions in principle, concerning the control as well as the retention of information. In more detail, it is the number of training sessions with acoustic feedback that need to be examined in order to keep the positive effects. Another aspect concerns the frequency with which the acoustic feedback should be used within a training session. Finally the time structure of the feedback training should be investigated that is, more precisely, the duration with information presentation in minutes.

In conclusion it is worth mentioning, that the potential of acoustic feedback and its positive effects found in the present study for training processes of elite rowers is neither restricted to the training of elite athletes not limited to the sport of rowing. It rather also seems to be promising for the field of recreational sports and, in particular, for rehabilitative processes in order to relearn a specific movement pattern after an accident or an injury.

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